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All-OPTICAL PULSE SWITCHING AND SHAPING BY A NONLINEAR SANDWICH

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Abstract

We demonstrate a simple model system comprised of a thin nonlinear layer sandwiched between two glass plates. This double Nonlinear Interface allows the investigation of both the transmitted and reflected beams for all-optical switching. Various potential applications of this Nonlinear Sandwich based on its intensity-dependent reflectivity and transmissivity are discussed. Focus is given to energy limiting, prepulse suppression, pulse shortening, and shaping. Experimental results show feasibility of these applications.

Introduction

The nonlinear interface (NI), comprised of a linear dielectric material in contact with an intensity-dependent nonlinear material, displays intensity-controllable reflection and transmission behavior.[1-4] The interest in the NI is partially governed by its potential application for all-optical switching and as optical logic elements.[4] Early NI experiments[2] showed crude switching performance due to the lack of a suitable model system with which the effects of the various parameters on the switching behavior could be easily explored. Only very recently[5] has such a simple model system been demonstrated. As the switching element, a thin nonlinear layer of an absorbing liquid sandwiched between two glass plates was used. Due to thermal expansion, this absorptive layer exhibits a negative nonlinearity as a result of density and related refractive index decrease. The nonlinearity can be quite large and may dominate over Kerr-like nonlinearity and electrostriction.[6]

This thermal Nonlinear Sandwich (NS), comprised of a double NI, allowed for the first time investigation of the spatio-temporal behavior of the transmitted and reflected beams simultaneously. Moreover, this device showed prevention of beam breakup and the high contrast switching performance, together with the near-Gaussian beam shape of both exit beams.[5] These results promise cascadability of such all-optical devices based on nonlinear interfaces.

In this paper we look into the possibility of various NS applications, such as energy limiting, prepulse suppression, pulse shortening and shaping, etc. We use the above-described thermal NS as a model system for the investigation. The response time of this thermal device is governed by the spot size of the incident laser beam and the sound velocity in the liquid; in the best case it is on the order of several nanoseconds and allows only a relatively low (depending on the amount of 'external' cooling) pulse repetition frequency. Nevertheless, it is a very powerful model system which requires relatively little hardware and which can be easily adapted to a large family of laser systems. In addition, since the switching performance depends on the ratio of the incident beams pulse length to the nonlinear materials response time (formation and relaxation time), the presented results are also valid in the ultrafast time regime when different nonlinear media are used. For example, the minimum thermal response time of ZnSe is on the order of 20 ps. With a saturable dye having an absorption cross-section of $\sigma = 5 \cdot 10^{-16}$ cm^2 and an intensity $I > 1.5$ GW/cm^2 incident on the interface, subpicosecond response time ($\tau \sim h\nu/\sigma I$) can be reached. Energy limiting with an NI using a saturable dye has already been shown with a 6 ps laser.[7]

Experimental

Figure 1 shows the experimental setup. The output of a frequency-doubled, Q-switched, diode-pumped YAG laser (ADLAS Lasers model DPY 301Q) was spectrally purified by a Corning 1-75 infrared blocking filter. This system delivered linearly polarized, 13-ns pulses [see Fig. 2-4 (top curves)] at 532 nm with a maximum energy of 12 μJ/pulse, at a repetition rate of up to 1 KHz. Approximately 9 μJ were available at the interface for switching. An achromatic lens with a focal length of 3.81 cm in air was used to focus the incident light at the interface to a theoretical 1/e amplitude radius of $\omega_0 \approx 5\,\mu m$. A beamsplitter reflected 8% of the incident light to a photodiode [EG&G FND-100Q, 2 ns response time] used to measure the temporal pulse shape of the light pulse incident on the nonlinear interface. A faster photodiode [Hamamatsu, R617, 300 ps response time] was used to measure the temporal pulse shapes of the spatially integrated (p/30) reflected and transmitted beams, because the other photodiode showed ringing at the faster signal changes. The signals from both detectors were sent to a fast oscilloscope [Tektronics 7104/7A25 with 1 GHz bandwidth] and photographed. The overall response time of the faster detection system was ≈ 0.5 ns. The pulse-to-pulse stability of the laser was ≈ 5%.

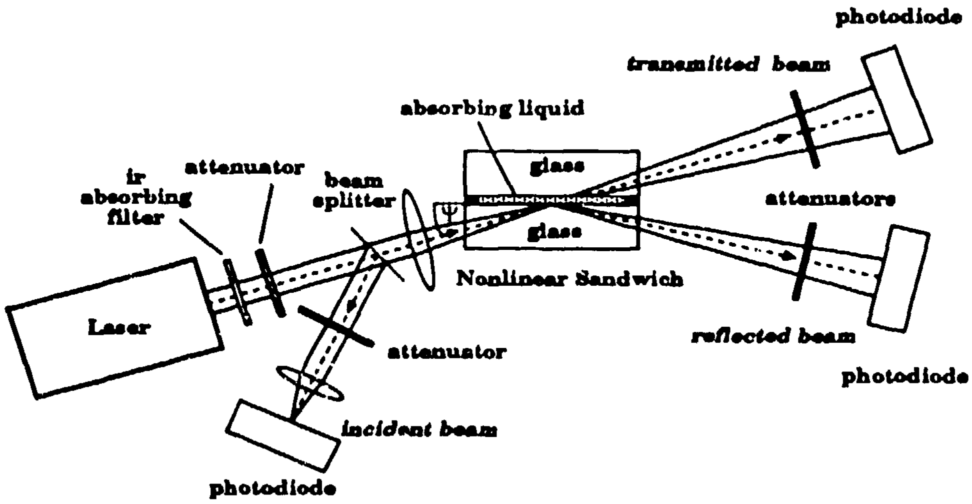

Fig.1: Experimental setup

The Nonlinear Sandwich (NS) used in the experiments is essentially a double Nonlinear Interface comprised of an absorbing liquid, as nonlinear media, sandwiched between two 1.3×4.5×9 cm^3 polished and unbeveled BK-7 rectangular glass plates (n=1.51947 @ 532 nm and 20° C) that formed the linear media. The fundamental limit of such a thermal liquid switch is governed by the spot size ($2\omega_0$) and the sound velocity (v) of the liquid. In our case, we estimate a response time [$\tau \approx \omega_0/v$] of 3 ns. The characteristic diffusion time can be estimated by using the relation of $\tau \approx \omega_0 2\rho Cp/4\kappa \approx 30\,\mu s$, with ρ representing the liquid density, Cp the specific heat at constant pressure, and κ the thermal conductivity. Note that the insulating glass plates will increase the effective decay time. However, for the switching performance, the time the system needs to return to the original starting (operating) temperature is more relevant than the intrinsic decay time. Therefore, without cooling and circulating the liquid, the average incident energy (repetition frequency) must be kept quite low to assure reproducible (low-power and high-contrast) switching performance.

The method used to produce the appropriate absorbing liquid has been described elsewhere.[5] We used a mixture of benzyl alcohol and ethylene glycol in which Naphtol Blue Black or low-molecular-weight Polyaniline were dissolved. The mixture was optimized to match as closely as possible the index of the linear medium (index mismatch $\Delta n < 2\cdot10^{-3}$) and had an absorption coefficient $\alpha \approx 50$ cm^{-1}. Similarly, other absorptive liquids will work. Nonfluorescing absorbers tend to be more suitable because

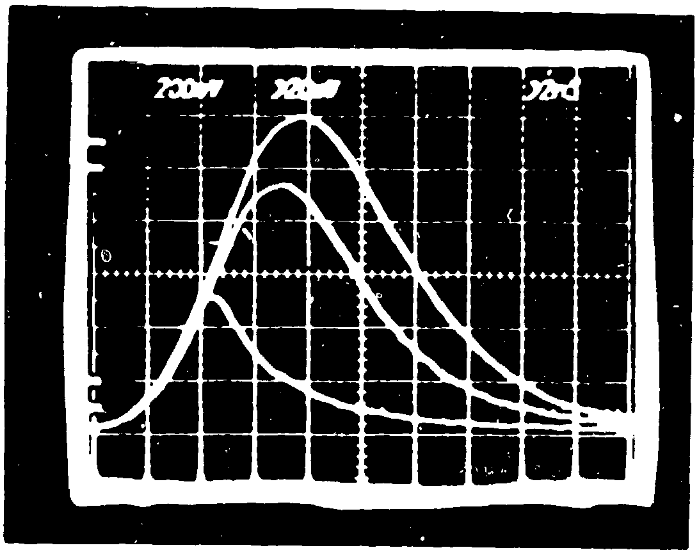

Fig. 2: Temporal pulse shape of the spatially integrated intensity measured with the thermal Nonlinear Sandwich at a glancing angle of 6°: The top curve shows the incident beam, while the middle and bottom curves show the transmitted beam for an incident beam energy of 0.9 mJ and 9 mJ. The curves are scaled to allow a better shape comparison.

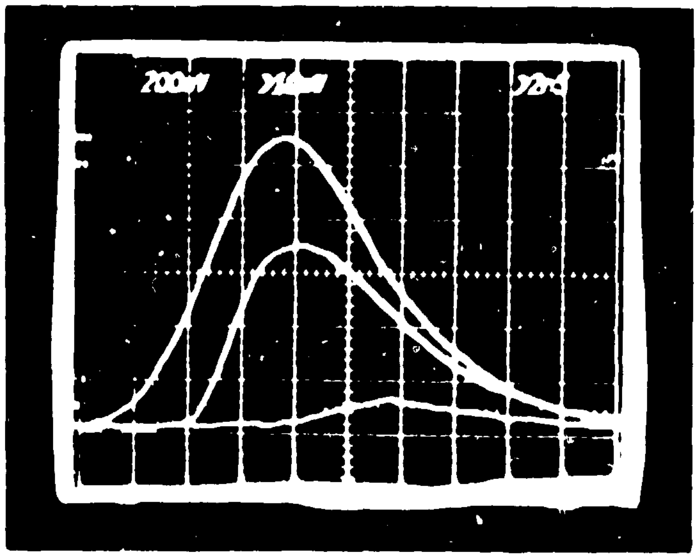

Fig. 3: Picture equivalent to Fig. 2 but for reflected beam (middle and bottom curve). The time scale is different: 2.63 ns/div.

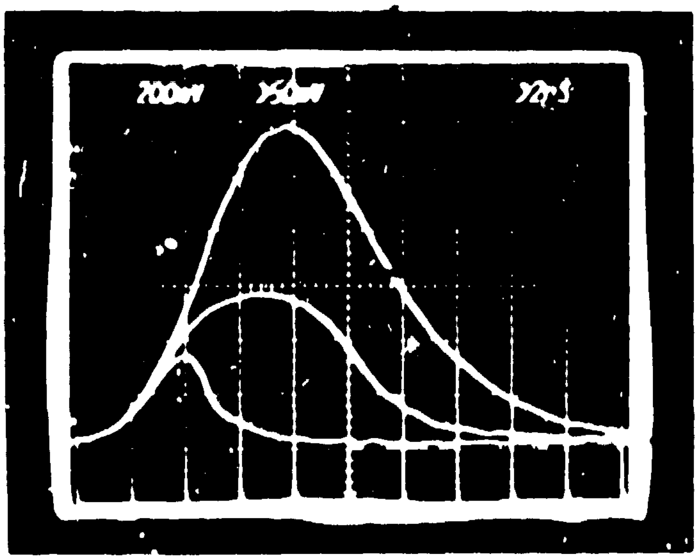

Fig. 4: Picture equivalent to Fig. 2 but with a spatially filtered transmitted beam. A pinhole allowed only the central 5% of the beam to reach the detector.

of their better photostability and higher efficiency of light to heat conversion. We chose Naphtol Blue Black or Polyaniline out of several substances we tested because they had a good photostability, an adequate extinction coefficient, and a negligible fluorescence. The former material proved to be even more photostable than the later one, allowing better long-term performance.

The ideal absorption depends on several conditions: for fixed-incident energy, higher absorption results in faster switching (until the fundamental switching speed limit is reached), and a smaller proportion of the incident energy is used to 'open' the switch. However, if too much energy is absorbed per unit volume, the local temperature can reach the boiling point of the liquid, resulting in bubble formation, thermal decomposition of the absorber, etc. Further, with increased absorption, the low-power reflection increases at all angles (see Fresnel formula). This reduces the obtainable contrast for the reflected channel. The transmitted channel is affected much less by this phenomenon. On the other hand, since the transmitted beam travels a much longer distance through the absorptive layer, as compared with the path of the total internal reflected beam, it is significantly more attenuated.

Results

Figures 2 and 3 show oscilloscope pictures of the typical time dependence of the incident (top curve) and the transmitted and reflected beams (middle and bottom curves), respectively, for different incident energies. The focus was optimized for fastest switching. For the higher intensity case, we find by comparing the areas under the curves that less than 1 μJ was necessary to 'open' the switch, i.e., to reach the switching threshold. The switch-on time is very close to the fundamental switching speed, estimated earlier to be 3 ns. The transmissivity of the NS is approximately constant for ~ 4 ns from the beginning of the incident pulse. Then it drops quickly to almost zero with a relative contrast of better than 50:1, limited by the noise of the detector. The reflected beam (Fig. 3) behaves in a complementary way, starting to switch with an ~ 4 ns delay from almost zero to its maximum. In the low-intensity case, we observe basically the same behavior, except that the delay time is longer and the transition from transmission to reflection is more gradual.

Figure 4 shows the time-dependent behavior of the central part of the transmitted beam. These pictures were obtained by spatially filtering the beam in such a way that only the central 5% of the transmitted beam reached the detecting diode. In the high-intensity case (9 μJ), we observe a shorter transmitted signal with the pinhole than without it (see bottom curve in Fig. 2). For the low-intensity case (0.9 μJ), the pulsewidth of the transmitted channel is approximately the same, but the beam shape is changed.

Discussion

Figures 2-4 show that, depending on the operating condition of the NS, different switching behaviors can be observed. The NS device can be simply described as a switching device that initially allows the incident light to exit the transmitted channel; then, after a time delay the incident channel is closed and the reflected channel is opened until finally all the incident light is redirected to the reflected channel. The minimum delay time before the switching from the transmitted to the reflected channel depends on the minimum response time of the chosen nonlinear material and on how fast a certain minimum switching energy is delivered (absorbed, in our case) to the nonlinear material. This behavior can be used for pulse shortening in the sense that the transmitted as well the reflected beams have shorter time duration than the incident beam. As Figures 2 and 3 show, this pulse shortening depends on the incident pulse energy: the higher the incident energy, the shorter the transmitted pulse and the longer the reflected one.

The reflected beam appears only after a certain energy has been delivered to the NS; thus, prepulse suppression is also possible. Consider the scenario in which the prepulse energy is transmitted through the NS and is simultaneously preparing the NS for the switching. When all the parameters are set correctly, the switch opens the reflected channel just when the main pulse arrives. An additional advantage of operation in this mode is the fact that the main pulse is spatially separated from the prepulse (for example, amplified spontaneous emission from a laser amplifier).

When a pinhole is used to spatially filter out the center part of the transmitted or reflected beam, we observe that under certain conditions the pulse shape is transformed from a near-Gaussian to a quasi–trapezoidal shape. The middle curve in Fig.4 displays such a behavior. A comparison with the middle curve in Fig. 2 (full beam) shows that, by simply placing a pinhole in the transmitted beam, one can control the 'flatness' of the transmitted pulse by changing the aperture diameter.

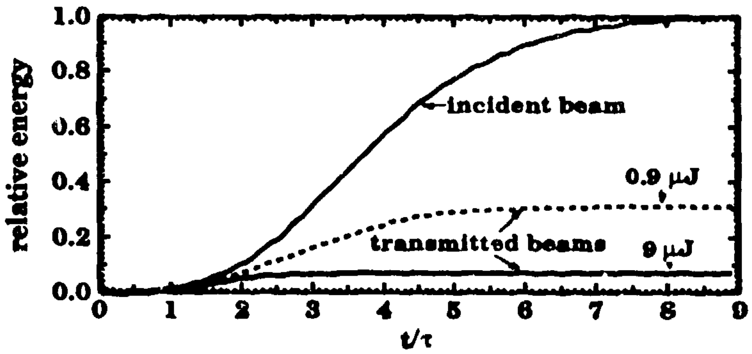

Fig. 5: Time dependence of the transmitted energy relative to the incident one measured for 0.9 μJ and 9 μJ incident energy. The glancing angle was 6°, and the timescale is normalized against the theoretical nonlinear material response time τ = 3 ns. The time dependence of the incident beam is also shown.

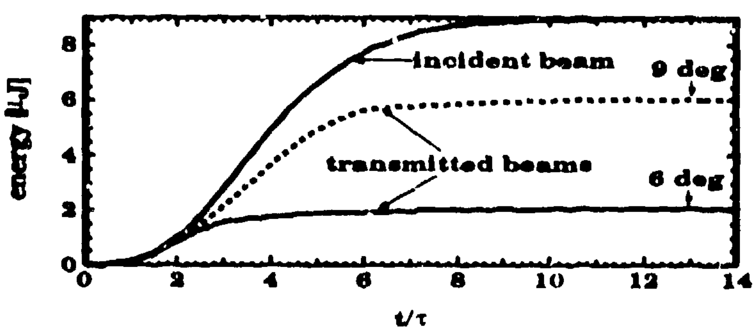

Fig. 6: Time dependence of the transmitted energy measured for glancing angles of 6° and 9°. The incident energy was 9 μJ.

Figures 5 and 6 show the time-integrated transmitted intensity for different incident energies and glancing angles. The transmitted channel of the NS has clearly an energy-limiting capability. The limiting energy depends on both the incident energy and the glancing angle. In fact, all of the above-described applications can be controlled both by the incident energy and by the glancing angle. The higher the glancing angle, the more energy has to be deposited before the switch opens, and the longer it takes for the switch to open for a fixed incident pulse. The angle dependence of the NS's switching point is very useful for fine-tuning of the chosen application.

The integrated beam quality of the reflected as well as transmitted beams has been shown[5] to be very good. This promises cascadability of NS devices and their possible application for all-optical computing.

Another possible application of NS is Q-switching of a laser: when placed inside a resonator, an NS changes its reflection with the incident radiation. This action is similar to that of a saturable absorber leading to modulation of Q-factor of the cavity. Note that the NS has more controllable parameters than the saturable absorber. Moreover, the intracavity NS can be used for self- termination of the laser pulse, leading to short pulse generation.

Conclusion

We presented several possible applications of the NS based on results obtained with a simple model system: a thermal NS. These results are not tied to the particular chosen model system. Performance in other time regimes can be deduced from these results if the material response time is appropriately scaled to the rise time of the incident pulse.

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